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SC-triggered plasma waves observed by the Akebono satellite in the polar regions and the plasmasphere

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Abstract: Plasma wave phenomena associated with sudden commencements (SCs) were analyzed based on observations conducted with the Akebono satellite, which has been collecting data for more than 13 years (since March 1989). Simultaneous plasma wave observation data for 257 SCs reveal that enhanced plasma waves are observed with an exact one-to-one correspondence with the SCs throughout the entire observation region, including the polar and plasmasphere regions. Electromagnetic whistler mode and ion cyclotron waves are enhanced in the low latitude plasmasphere, while electrostatic whistler mode and electromagnetic ion cyclotron waves are generated in the polar region. The onset times of the SC-triggered plasma waves exhibit a delay or lead time characteristic, compared with the onset times of SCs identified by the Kakioka Magnetic Observatory, with a time resolution of 1 s. By comparing the difference in SCs and enhanced electron plasma waves onset times, the propagation route of the SC disturbances can be identified in the plasmasphere.

1. Introduction

The generation and enhancement of plasma waves in the ULF-VLF range has been reported to be associated with sudden commencements (SCs). Tepley and Wentworth (1962) reported an intensification and an increase in the frequency of Pc1 ULF waves associated with SCs. Kokubun and Oguti (1968) pointed out that SC-triggered ULF events tend to appear in the morning-noon sector. Hirasawa (1981) demonstrated a clear local time dependence of SC-triggered Pc1 ULF waves. However, the possible effect of the ionosphere depending on the local time has not been evaluated using the ground-based observations. Morozumi (1965) reported that SC-triggered VLF chorus emissions also occur. Hayashi *et al.* (1968) reported an increase in the frequency of VLF chorus emissions about 30 s or more before the onset of SCs. They attributed the change in the VLF spectra to variations in temperature anisotropy caused by an abrupt increase in the geomagnetic field.

Satellite observations are necessary to clarify the distribution of SC-triggered plasma waves in the magnetosphere, plasmasphere and polar regions without the influence of ionosphere conditions. Mullayaov and Yachmenev (1990) reported the enhancement of whistler mode plasma waves observed based on observations obtained with the GEOS-2 satellite. Gail and Inan (1990) studied 14 VLF emission events observed by the DE1 satellite. However, time resolution limitations (32 s for the DE data) make it difficult to analyze SC-triggered VLF emissions in detail.

In this paper, ELF-VLF plasma wave phenomena associated with SCs are examined using data records collected by the Akebono satellite plasma wave instruments over a 13-year period. The purpose of the present study is to identify the generation of plasma waves associated with SC disturbances in the polar region and the plasmasphere. The study also attempts to use the high-time resolution data obtained from the Akeobon satellite to clarify the relationship between the onset of SCs identified on the ground and the modification of energetic particles and the plasma waves in order to understand how the plasma waves and particles in the polar region and plasmasphere respond to SC disturbances.

2. Observation data

The Akebono satellite has been continuously conducting observations for more than 13 years. The satellite was launched on February 21, 1989, and placed in a semi-polar orbit with an inclination of 75° and an initial apogee and perigee of 10500 km and 274 km, respectively. In the present series of studies, the plasma wave data was obtained by the PWS (20 kHz-5.1 MHz) (Oya *et al.*, 1990), VLF (3.16 Hz-17.8 kHz) and ELF (0 Hz-80 Hz) (Kimura *et al.*, 1990) instruments onboard the Akebono satellite. The plasma wave data analysis was combined with an analysis of low energy particle data obtained by the LEP (Mukai *et al.*, 1990) instrument, also installed on the Akebono satellite. The time resolution of the dynamic PWS spectra is 2 s, while the time resolution of the VLF, ELF, and LEP data is 8 s, as specified by the Akebono satellite data-base.

3. Identification of SCs

Between March 1989 and November 2001 (Table 1), 930 SC events were identified in the SYM-H data (Iyemori and Rao, 1996), which has a time resolution of 1 min. SC events were identified by a rapid increase in SYM-H values (more than 5 nT within 10 min). For each SC event, the precise onset time was identified by referring to the H-component of the geomagnetic variation measured at the Kakioka Magnetic Observatory; the time resolution of the H-component measurement is 1 s. As shown in Fig. 1, the onset time of the SCs can be identified with a time resolution of 1 s. In Fig. 1, the SYM-H data shows an increase of 23 nT per ten minutes from 1222 (UT) on September 22, 1999. The simultaneous H-component geomagnetic variation measured at the Kakioka Magnetic Observatory indicates that the increase in the geomagnetic field started at 1222:03 (UT). Thus, the onset times of the SCs can be identified with a time resolution of 1 s. Within the 13-year period of the Akebono satellite operation, from March 1989 to November 2001, two-hundred and fifty-seven PWS observation periods corresponded with the onset time of an SC event. In all the observation cases, a clear plasma wave signature (involving a change in intensity or frequency spectra) appeared in response to each SC. Table 2 shows the event list of these SC-triggered plasma wave phenomena, as observed by the PWS instruments onboard the Akebono satellite. As shown in Fig. 2, the SC-triggered plasma wave events do not have a clear dependence on the geomagnetic local time, altitude or

Table 1. SC event list from March 1989 to June 2001, based on the SYM-H index provided by the WDC-C2 for Geomagnetism.

year \ month	1	2	3	4	5	6	7	8	9	10	11	12
1989			10	3	7	7	3	9	11	6	8	6
1990	4	4	4	6	7	4	9	5	3	3	1	4
1991	3	3	11	5	7	23	12	10	1	9	6	6
1992	11	12	2	4	6	8	1	9	6	4	5	5
1993	5	5	11	7	3	3	4	5	3	7	6	3
1994	1	2	0	3	2	1	3	2	0	6	2	4
1995	2	1	3	4	5	1	4	8	1	4	4	4
1996	4	4	0	6	6	4	6	4	3	5	6	5
1997	4	4	5	5	5	5	6	3	5	6	7	2
1998	8	0	6	7	9	12	16	11	8	9	6	5
1999	3	7	2	2	6	7	6	5	8	5	5	3
2000	2	8	5	6	7	17	18	7	11	12	17	4
2001	13	4	15	18	12	4	3	16	11	21	10	

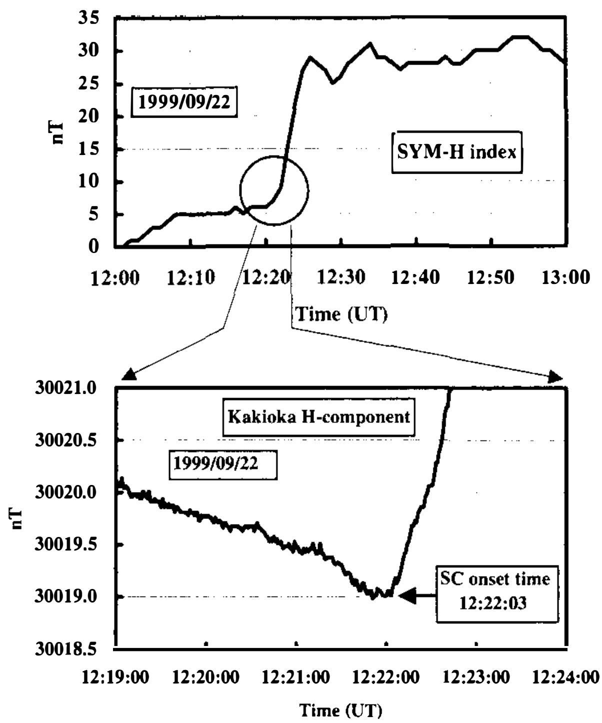

Fig. 1. Identification of the onset of an SC event on September 22, 1999. The SYM-H data shows an increase with a speed of 3.8 nT per ten minutes starting at 1222 (UT). The onset time was identified as 1222:03 (UT), with an accuracy of 1 s, based on the H-component geomagnetic variation observed at the Kakioka Magnetic Observatory.

Table 2. List of SC-triggered plasma wave phenomena observed during the PWS experiment.

year \ month	1	2	3	4	5	6	7	8	9	10	11	12
1989			5	3	3	1	1	5	3	2	4	5
1990	1	0	3	3	3	1	5	2	3	1	0	1
1991	1	1	5	3	2	8	7	7	0	4	3	0
1992	2	6	1	3	0	2	1	5	2	0	0	0
1993	1	2	3	3	2	1	0	1	2	3	4	0
1994	1	1	0	1	1	0	3	2	0	3	0	2
1995	1	0	1	0	1	1	0	4	0	1	1	1
1996	0	2	0	5	1	1	2	1	0	0	2	0
1997	0	1	1	0	3	1	0	0	3	1	0	0
1998	3	0	0	2	2	4	2	2	1	3	1	0
1999	0	0	0	1	3	1	3	0	4	2	1	0
2000	0	4	3	1	3	1	2	2	4	1	3	2
2001	6	0	2	0	0	0	1	3	0	0	1	

geomagnetic latitude, however, as will be shown in the next section, their propagation modes show a clear dependence on the geomagnetic latitude of the observation point. Therefore, the appearance of plasma wave phenomena corresponded exactly with that of the SCs in any observation region within the plasmasphere, inner magnetosphere and polar ionosphere for each SC event observed during the period of the Akebono satellite's operation.

4. Plasma waves associated with SCs

4.1. Example of a low latitude (Mlat $<45^{\circ}$) event

Figure 3 shows an example of an SC event that occurred at 0720:30 (UT) on March 30, 1990, when the Akebono satellite was located in a low geomagnetic latitude region of the plasmasphere. The dynamic spectra of the VLF plasma waves show a clear intensification associated with the SC near the LHR (lower hybrid resonance) frequency of about 5 kHz. The frequency spectrum of the LHR wave increases above the LHR frequency, with a rising tone signature. The VLF spectra show that the intensity of the plasma waves peaks near the LHR frequency. The enhancement of the VLF plasma waves lasts for about three minutes after the onset of the SC. In this case, a lead time of 40 s in the PWS data was found by comparing the onset time of the enhancement of the whistler mode plasma waves with that of the SC, based on observations performed at Kakioka. In the ELF range, the generation of ion cyclotron waves can be seen above the helium cyclotron frequency, near the oxygen cyclotron frequency. The enhancement of the ELF plasma waves lasts for more than fifteen minutes after the onset of the SC. The onset of the ELF plasma waves occurred about 30 s after the onset of the VLF plasma waves.

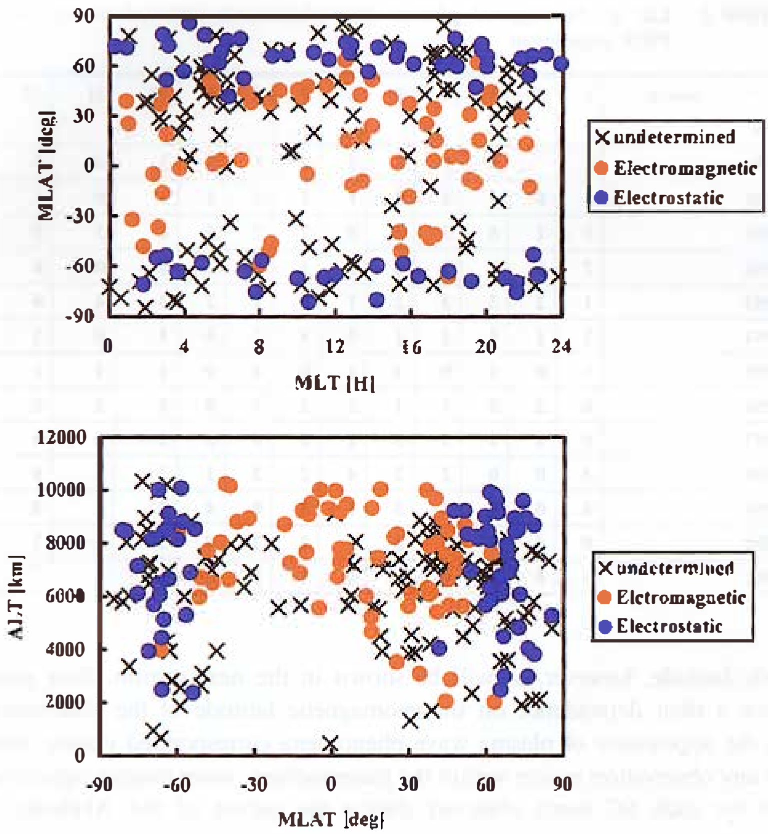

Fig. 2. Distribution of SC-triggered events observed by the Akebono satellite. In the upper panel, the events are plotted with the geomagnetic local time versus the geomagnetic latitude. In the bottom panel, the events are plotted with the geomagnetic latitude versus the altitude. Red and blue circles represent the propagation modes of the SC-triggered plasma waves in the whistler mode frequency range, identified as the electromagnetic and electrostatic modes, respectively. The crosses represent SC-triggered plasma wave events whose propagation mode could not be determined because of missing magnetic field spectra data.

4.2. Example of a high latitude (Mlat > 45°) event

Figure 4 shows an example of an SC event that occurred at 0325:52 (UT) on April 12, 1990 when the Akebono satellite was located in the dayside cusp region. The plasma wave phenomena appear simultaneously with the SC within the 1 Hz to 90 kHz frequency range. Within the frequency range extending from the LHR frequency to the electron cyclotron frequency, the whistler mode plasma waves clearly corresponds with the onset of the SC. The onset of whistler mode plasma wave enhancement occurred at 0325:32 (UT), with a 20-s lead time prior to the onset of the SC. By comparing the intensities of the electric and magnetic fields of the plasma waves, the present plasma wave can be shown to exhibit an electrostatic feature. In general, SC-triggered plasma waves in the whistler mode frequency range resemble the electrostatic whistler mode in the polar region. On the

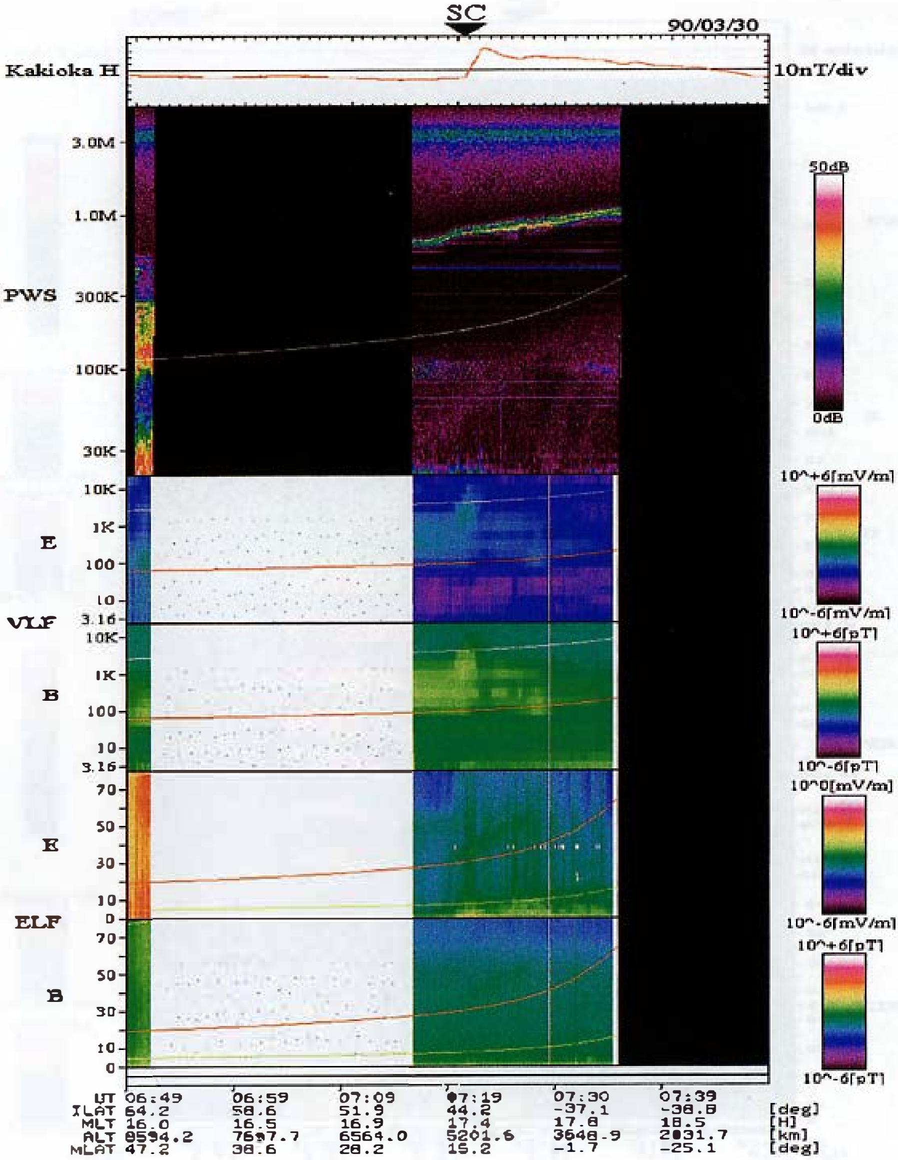

Fig. 3. Example of an SC event occurring at 0720:30(UT) on March 30, 1990, when the Akebono satellite passed through a low-latitude plasmosphere region. The top panel shows the geomagnetic data provided by the Kakioka observatory; the second panel shows the PWS electric field plasma wave spectrum from 20 kHz to 5.1 MHz, with the white line indicating the electron cyclotron frequency; the third and fourth panels show the VLF electric and magnetic field plasma wave spectra from 3.16 Hz to 17.8 kHz, with the white and red lines indicating the LHR and proton cyclotron frequencies, respectively; the fifth and sixth panels show the ELF electric and magnetic field plasma wave spectra from 0 Hz to 80 Hz, with the red and yellow lines indicating the helium and oxygen cyclotron frequencies, respectively. The enhancement of the electromagnetic whistler mode plasma wave can be seen near the LHR frequency, and the enhancement of the ion cyclotron wave can be seen near the helium frequency in association with the SC.

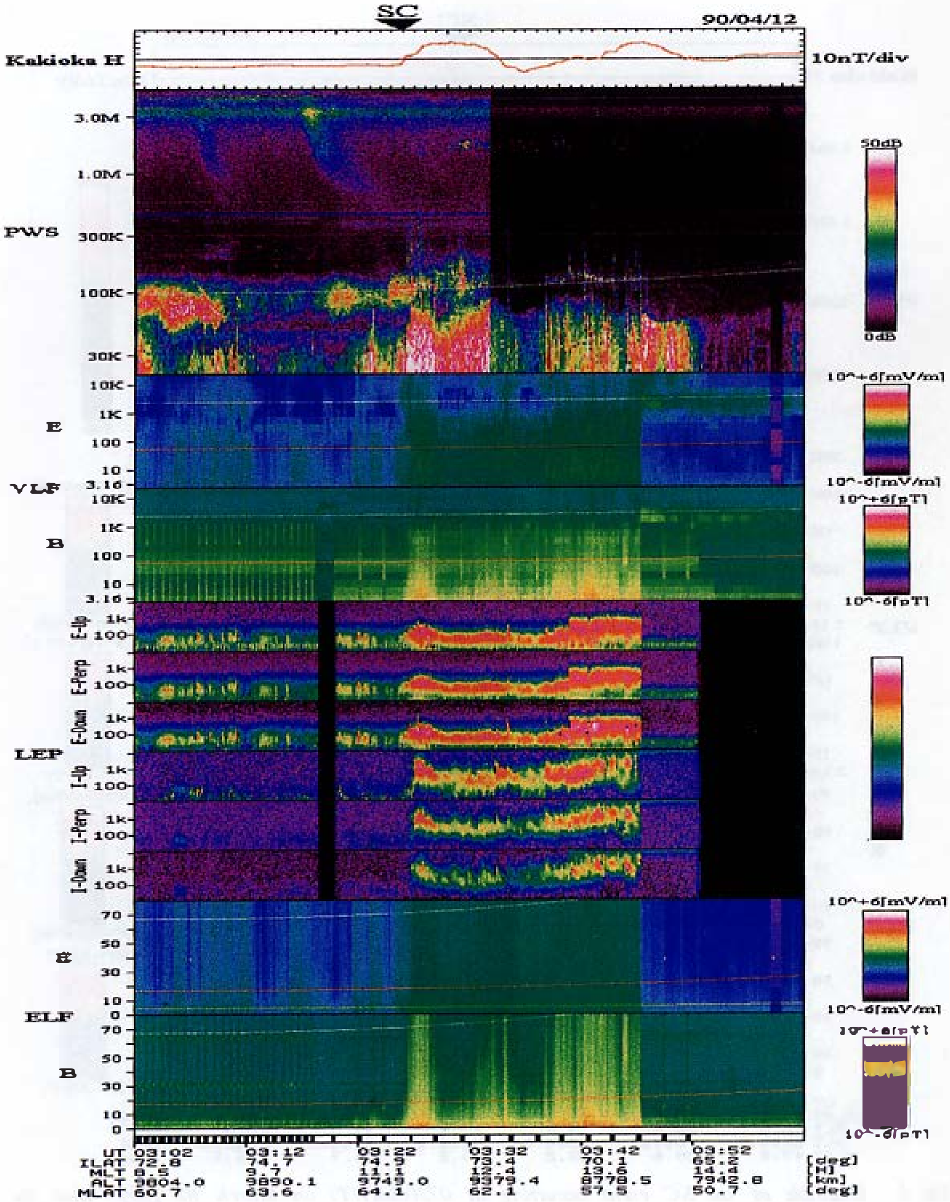

Fig. 4. *Example of an SC event occurring at 0325:52(UT) on April 12 1990 when the Akebono satellite passed through the cusp region. The formats of the PWS, VLF and ELF spectra are the same as in Fig. 4. The fifth to tenth panels show the LEP data of the electrons and ions for the pitch angles of three sectors and an energy range of 10 eV to 20 keV. In the LEP spectra, 'E-Up', 'E-Perp', and 'E-Down' indicate the electron spectra for the pitch angle ranges of 0°–60°, 60°–120°, and 120°–180°, respectively, followed by the ion spectra for the some pitch angle ranges as for the electrons. Pitch angles of 0° and 180° correspond to the downward and upward directions along the magnetic field line, respectively, since the Akebono satellite is located in the northern hemisphere. In the ELF spectra, the white line shows the proton cyclotron frequency. The enhancement of whistler mode plasma waves and particle fluxes in association with the SC is shown.*

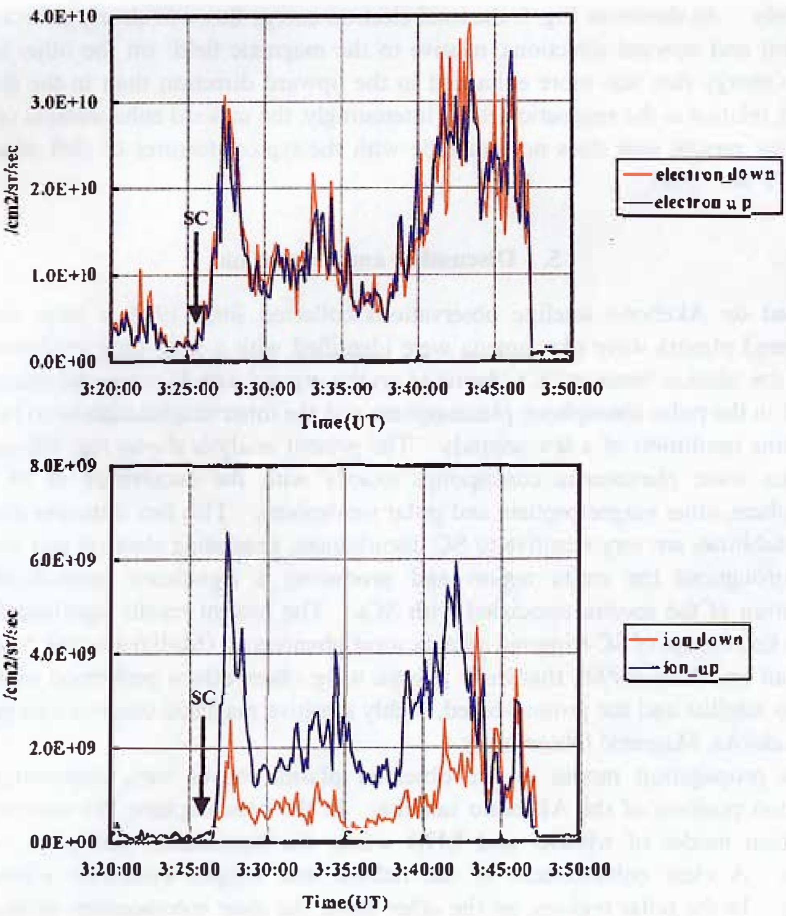

Fig. 5. *Total energy fluxes of the upward and downward components of the electrons and ions obtained for the same time period as in Fig. 4. The total electron energy flux is clearly enhanced in the downward and upward directions, relative to the magnetic field in association with the SC; on the other hand, the ion total energy fluxes are more enhanced in the upward direction than in the downward direction, relative to the magnetic field.*

other hand, the electromagnetic whistler mode is seen in the low latitude region inside the plasmasphere, as shown in Fig. 2. In the ELF range below 10 Hz, ion cyclotron waves with a magnetic field that is stronger than the electric field intensity are generated near the helium and oxygen cyclotron frequencies. The onset of these enhanced ion plasma waves occurs about 30 s after the SC.

Low-energy electron and ion spectra were available for Akebono satellite observations performed in the high latitude regions. Figure 4 also shows a clear enhancement of low energy electrons and ions associated with the SC-triggered plasma wave phenomena. In the LEP data, the electrons are enhanced in all the pitch angle sectors at 0325:32 (UT) near 80 eV. On the other hand, the ions are enhanced at 0326:52 (UT) near the 1-keV energy range. The enhanced electrons and ions exhibit a peak energy of 800 eV and 10 keV, respectively. As shown in Fig. 5, the total electron energy flux was clearly enhanced in the downward and upward directions, relative to the magnetic field; on the other hand, the total ion energy flux was more enhanced in the upward direction than in the downward direction, relative to the magnetic field. Interestingly, the upward enhancement of the keV ions in the present case does not coincide with the typical features of cleft observations (Mukai *et al.*, 1990).

5. Discussion and conclusion

Based on Akebono satellite observations collected since 1989, a large number of SC-triggered plasma wave phenomena were identified with a high time resolution. This enabled the relation between SCs identified on the ground and SC-triggered plasma waves observed in the polar ionosphere, plasmasphere and the inner magnetosphere to be clarified with a time resolution of a few seconds. The present analysis shows that the occurrence of plasma wave phenomena corresponds exactly with the occurrence of SCs in the plasmasphere, inner magnetosphere and polar ionosphere. This fact indicates that plasma wave instabilities are very sensitive to SC disturbances, generating electron and ion plasma waves throughout the entire region and producing a significant intensification and modification of the spectra associated with SCs. The present results significantly extend previous knowledge of SC-triggered plasma wave phenomena (Mullayaov and Yachmenev, 1990; Gail and Inan, 1990), thanks to plasma wave observations performed onboard the Akebono satellite and the ground-based, highly sensitive magnetic observations performed at the Kakioka Magnetic Observatory.

The propagation modes of the observed plasma waves vary, depending on the observation position of the Akebono satellite. In the plasmasphere, the electromagnetic propagation modes of whistler and LHR waves are significantly enhanced over long distances. A clear enhancement of the helium and oxygen cyclotron waves is also apparent. In the polar regions, on the other hand, the clear enhancement of electrostatic whistler mode plasma waves is observed over a wide frequency range. The enhancement of electromagnetic ion cyclotron waves in association with SC disturbance is also visible.

By examining the time difference between the onset times of SCs and the enhancement of electron plasma waves, the propagation characteristics of the SC-triggered disturbances can be identified. A detailed analysis of SC-triggered plasma waves could be used to determine the nature of the propagation of SC disturbances in the plasmasphere and polar regions. The results of this delay-time analysis will be described in a future report. Since sufficient satellite observations in the plasmasphere have not yet been obtained, the observation of high-energy particles should be included in future satellite observations performed in the plasmasphere.

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